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Terrestrial Locomotion Modeling Bio-inspired by Elongated Animals

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Abstract

This paper presents a unified dynamic modeling approach of bio-inspired continuum robots. The resulting algorithm exploits a continuous version [1] of the Newton-Euler models of discrete structures and, is capable of computing the net motions as well as the internal control torques (and/or forces) of the continuum robot. The illustrative examples show that how this dynamic model work with the kinematic constraint model in order to produce locomotion. The efficiency of the algorithm is finally illustrated through examples related to the terrestrial locomotion of elongated animals such as snakes and worms.

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Keywords: Beam theory; Continuum robots; kinematic constraints; Newton-Euler dynamics

1. Introduction

This work takes inspiration from enormous terrestrial locomotion of elongated animals including both vertebrates and invertebrates. In robotics, such inspiration has led the researchers to develop continuum robots such as hyper-redundant and soft-bodied robots. Their dextrous locomotion capabilities and slender morphologies play a crucial role to attain search and rescue missions in unstructured and confined environments. To describe and demonstrate the terrestrial locomotion phenomenon we introduce a modeling paradigm based on the geometrically exact beam theory of J.C. Simo. This dynamic model of a $3D$ continuum robots provides solutions in a unified theoretical framework which is still a challenge for robotics. The kinematic constraint model presented here is a continuous version of the finite-dimensional kinematic connections of nonholonomic mechanics.

2. Modeling Approach

In this approach the robot is modeled as a Cosserat beam i.e., a multi-body system made of an infinite number of bodies (cross sections) of infinitesimal length assembled along the line of their centroids. Furthermore, due to an imposed strain law, the cross sections move with respect to one another and the inter-cross-sectional kinematics represent a joint of a conventional (discrete) multi-body system. Once related to the general theory of locomotion on principal fiber bundles, such a model is used to solve two important problems of robotics: 1) to compute the net motions of the leading body (e.g. head of the elongated animal) and, 2) to compute the internal control torques. This model naturally splits into three continuous sub-models: 1) a kinematic model of cross-section transformations, velocities and accelerations, 2) a dynamic model of the internal control torques and/or forces represented as the partial differential equations of the actuated beam and, 3) according to the principal fiber bundle structure of the configuration space, a dynamic model of the robot in the fiber, named ”locomotion dynamic model”. In this work, we consider a wider

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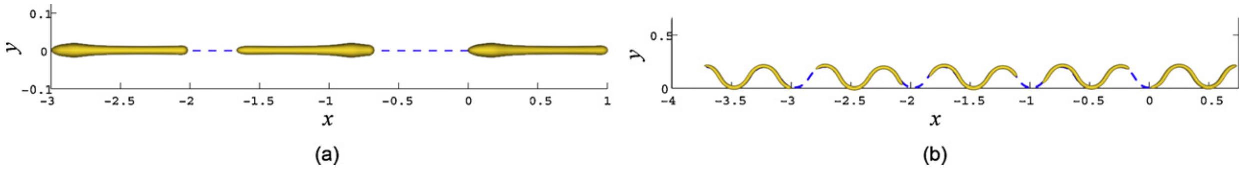

Fig. 1. (a) Earthworm locomotion; (b) Snake locomotion

context where the internal strain laws are arbitrary. The external forces responsible for the propulsion are imposed by the contact with the terrain and, modeled through constraints. In this case, due to the relative number of constraints compared to the number of degrees of freedom of the net motions, the locomotion dynamic model degenerates into kinematic model.

The nature of contact plays an important roll in defining the mode of locomotion. Based upon the terrestrial contact of elongated animals, we deal with two types of contacts (assumed ideal): anchorages and supports. Anchorages are modeled as bilateral holonomic constraints while supports are modeled as non-holonomic constraints. In both cases the contacts are distributed along the body axis. Moreover, the contact forces are identified as Lagrange multipliers associated to the constraints.

3. Illustrative Examples

3.1. Burrowing Worm in 1D

This is a burrowing robot inspired by earthworms. The earthworm is assumed to have a homogenous volumetric mass. Based on biological knowledge, the radial dilation of the sections caused by axial compression ensures the worm's interactions with earth here modeled as sweeping anchorage. Locally, the radial anchorage is achieved by rigid setae which push into the earth radially when the section is at maximal dilation. This natural phenomenon is modeled as beam in traction-compression. The forward motion is produced by a traction-compression wave. The dilation of the sections is controlled by the traction by adding the volume preservation constraint to the Cosserat theory. For numerical illustration of earthworm locomotion, a sinusoidal gait is introduced into the general algorithm. We get the straight line $1D$ motion of the worm in the xy plane as shown in Fig. 1(a). By taking the celerity constant, it is noted that the axial contact force is zero at the anchorage point.

3.2. 2D Snake in Lateral Undulation

An other interesting terrestrial locomotion mode that has been inspired the robot researchers is the lateral undulation of a snake. This mode can be modeled either as a Kirchhoff or as a Reissner planar beam. In this illustrative work, we choose the Kirchhoff-snake kinematic model that corresponds to the ACM-III robot of Hirose [2]. In lateral undulation, the snake supports itself laterally in its environment to self propel in an axial direction. Mathematically, these supports are modeled as nonholonomic constraints preventing the snake to slide laterally. In the case where the contact with the terrain is continuously distributed along the body length, there are obviously enough of these constraints for the external movements to be completely fixed by the internal kinematics of the snake and thus to be defined by a principal kinematic connection on the principal fiber bundle. By incorporating these nonholonomic constraints in the velocities, we note that the axial speed of the snake is constant with respect to X and thus equal to that of its head. For illustration, an undulatory gait is imposed as input to the algorithm. The simulation gives a $2D$ motion of the snake in the xy plane as shown in Fig. 1(b).

4. Conclusions

In this work, we have proposed a unified modeling approach of the emerging domain of continuum robots. The approach as a whole is applied to the case of terrestrial locomotion illustrated with examples. Through these examples, the algorithm shows its efficiency and the easiness of its use when it is applied to the locomotion analysis or gait generation. One of the perspectives concerns the adaptation of the theory to internal actuation principles not well adapted to the Cosserat assumption, as it is the case of complex hydrostats such as the octopus arms.

References

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